Modeling the Kinetics of Cooking and Precooking Potatoes

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ABSTRACT

This research investigated the kinetics of cooking potatoes over the temperature range in which starch gelatinizes. A back extrusion texture test was used to measure cookedness. By correlating the data with that of other researchers using different texture tests and potato varieties, we present a unified model of cooking which is first order, independent of variety, and applies to both cooking and gelatinization over the temperature range of 74°C to 100°C.

INTRODUCTION

WE ARE DEVELOPING the methodology for a systems study of potato processing using the potato flake process as the prototype for the development. Mathematical models are needed for the simulation of the individual unit operations e.g. precooking (hot water blanching) and cooking. Precooking is a unit operation in which potatoes are heated in hot water at 60–85°C for up to 20 min (Talburt and Smith, 1967). In this temperature range the potato starch undergoes gelatinization and the potato cooks very slowly. During gelatinization amylose diffuses out of the starch granule, Smith (1980). The remaining amylopectin in the granule absorbs water swelling the granule. There is little cell wall distention under these conditions of temperature and time (Reeve, 1953).

Following precooking, the potatoes are cooled in the commercial process in water (preferably maintained below 24°C) for up to 15 min. (Talburt and Smith, 1967). This causes the starch to retrograde; the straight chain amylose crosslinks becoming insoluble giving the potato cell a firm structure which remains intact through cooking, drum drying, and rehydration (Smith, 1980).

Following precooking and cooling in the commercial process potatoes undergo steam cooking. Proper cooking softens the potato tissue sufficiently to mash without destroying the cell structure (Anon, 1959). An objective, quantitative test and model of cooking is needed.

Harada et al (1985) cooked three potato varieties, Bintje, Mentor and Desiree, at 90°, 100°, and 110°C and found cooking as measured by changes in texture and taste can be described by a zero order relationship. They also showed that changes in shear force (which is an objective rather than sensory measurement of cooking) can be described by a first order equation. They used a Zwick universal testing machine. Kiyoshi et al. (1978) also studied the effect of cooking potatoes at 80°, 85°, 90°, 95°, and 99.5°C on texture. Although their rate equation was slightly different in form, it was still basically first order. They studied potatoes of undetermined variety with an unspecified impact-penetration tester.

The objective of this paper is to develop texture or softening data for gelatinization as well as for cooking in the range of starch gelatinization; and, using literature data and our data, to develop a unified kinetic model for cooking and precooking which is independent of variety and the type of texture measurement.

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MATERIALS & METHODS

FOUR VARIETIES of potatoes were used—Russet Burbank and Red Pontiac from Maine, Norchip from North Dakota, and Atlantic from Florida. Texture tests were performed on the freshly received potatoes and after periods of storage up to 6 months at 3°C, up to 6 months at 13°C, and at room temperature, 20—25°C, up to 3 months. Some lots were shifted from one storage to another before testing.

The potatoes were abrasion peeled, trimmed, and diced with an Urschel cutter Model RA (Urschel Laboratories Inc., Valparaiso, IN) to make 9.5 mm cubes. They were then soaked in a 0.5% solution of $NaHSO_3$ for 2 min.

To study precooking and cooking, about 500g potato dice were placed in a wire basket and into a water bath kept at 74°, 76.5°, 79°, or 85.5°C. Time was recorded from the time the potatoes went into the water. The wire basket was removed at a predetermined time, up to 60 min, and placed in a 27°C water bath for 3 min to standardize the temperature of the potatoes in the texture test. The potatoes were drained and held at room temperature until completion of the texture testing, which took about 10 min.

A Food Texture Corp. testing machine, model TP2 (Food Texture Corp., Rockville, MD) with a Model FTA-300 force transducer was used for the texture measurements. We used a back extrusion test cell because a sample (approximately 85g) consists of many individual pieces giving a statistically representative sample. The test cell, built in-house, was 53.2 mm diameter and 76.2 mm deep. The piston was 45.2 mm diameter resulting in an annular clearance of 4 mm. The stroke depth was 65.1 mm (11.1 mm bottom clearance) and the stroke rate was 6.8 mm/sec. Six to eight tests were made on each batch of cooked potatoes. All cooking experiments performed on a specific lot of potatoes at specific conditions were done on the same day to minimize the effect of ambient conditions on the experiments. Maximum force readings in the tests were recorded (Bourne and Moyer, 1968).

In addition to the above test procedures combining precooking and cooking in one hot water bath, cooling tests were also run after the time equivalent to precooking to measure the change in texture after retrogradation of the gelatinized starch. The texture testing procedure was as above except the potatoes were placed in an ice water bath for various periods of time after the hot water bath and before standardizing the potatoes in the 27°C bath.

RESULTS & DISCUSSION

THERE ARE 17 SETS of data relating texture force to time of heating in a water bath at four temperatures for various storage histories and potato varieties. A semilog plot of texture as measured by peak force as a function of temperature of five representative sets is shown in Fig. 1. In these experiments the cold potatoes lowered the bath temperature several degrees and it took 4 to 8 min for the bath to recover to the test, or set, temperature. The basket of potato dice is not a regular piece size or shape readily amenable to calculation of thermal lag. The appropriate equation for dice, infinite slab, or sphere chosen to correct for thermal lag, would require an experimentally determined correction factor, such as porosity. To estimate the time for heating the potato dice, Eq. (1) from Carslaw and Jaeger (1959) was used with a thermal diffusivity of potato at 1.5 × 10^{-7}m²/sec. (Harada et al., 1985).

$$\frac{T_1 - T_i}{T_1 - T_0} = 2 \sum_{n=o}^{\infty} \frac{(-1)^n}{\left(n+\frac{1}{2}\right)\pi} \exp \left[- \left(n+\frac{1}{2}\right)^2 \pi^2 \frac{\alpha\theta}{B^2} \right] \cos \left(n+\frac{1}{2}\right) \pi \frac{x}{B} \quad (1)$$

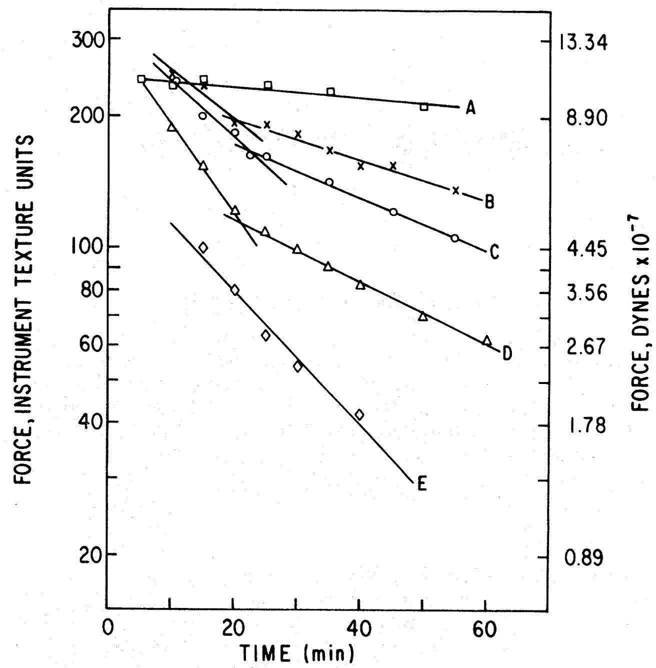

Fig. 1—Plot of peak force (instrument texture units) vs time with potato variety and temperature as parameters. Texture units on the right y axis are the equivalent metric units in Dynes × 10^{-7}. Line A—Russet Burbank potatoes tested at 74°C; line B—Norchip potatoes tested at 74°C; line C—Russet Burbank potatoes tested at 79°C; line D—Norchip potatoes tested at 79°C; and line E—Norchip potatoes tested at 85.5°C.

This calculation indicated the potato dice temperature, T_i, reached within 0.3°C of the bath temperature T_1, in 6 min, θ. This lag would alter the curves in Fig. 1 in the first few min. However, since this thermal lag was reasonably consistent for all points on the curve in the first few minutes, it would affect all points on a curve equally and the slope of the curves would remain unchanged. Ultimately the model developed will utilize the fractional change in texture force as a measure of the amount of cooking which requires only the slope. Therefore, no corrections for thermal lag or heat-up time were made.

A retrospective check was made of this assumption. The texture change was calculated using the model; assuming instantaneous heating to bath temperature and by calculating the temperature during heat up using Eq. (1). After 5 min the model results indicated an error of 0.7% or less (8×10^5 dynes or 1.8 instrument units).

In the temperature range of these tests, 74–85.5°C, potatoes undergo starch (amylose) gelatinization. They also cook slowly. It was tentatively assumed that the second part of these curves (flatter slope) reflected cooking whereas the first part (steeper slope) involved cooking plus gelatinization. This would explain the break in three of the lines—B, Norchip at 74°C; C, Russet Burbank at 79°C; D, Norchip at 79°C—in Fig. 1. However, the slope of line E, the Norchip potatoes at 85.5°C, was of the correct magnitude for cooking but not cooking plus gelatinization. Gelatinization probably reached equilibrium or was complete before it could be measured. In several experiments there was no detectable gelatinization, as shown by line A, the Russet Burbank potatoes at 74°C.

These data, plus those not shown, fit a first order equation of the form:

$$-\frac{dF}{d\theta} = k\,F \qquad (2)$$

where F is the peak texture force. The correlation coefficients averaged 0.92 ($r^2 = 0.85$) for the 17 sets of data. Integrating Eq. (2) we get:

$$-\ln F/F_O = k\theta \qquad (3)$$

where F_O is the estimated initial or raw potato texture and k is the rate constant. F_O was not measured directly but was calculated by back extrapolation.

The initial texture, F_O, and the texture, F, will vary depending on the variety and lot of potatoes (Harada et al., 1985). But, the rate of change of the dimensionless quantity, F/F_O, in Eq. (3) should not be affected by the variety or lot (Pravisani and Calvelo, 1986). If true, the rate constant, k, should be independent of texture test or variety. To test this, we employed texture test data from three different texture testing machines. The specific testers were unimportant—only that they were different and accurately measured the texture of potatoes. Kiyoshi et al. (1978) used an impact-penetration tester on slices. Harada et al. (1985) used a Zwick universal testing machine on slices. We used an FTC back extrusion tester on dice. Therefore, we calculated the rate constants from the data of Kiyoshi et al. (1978), used the constants from Harada et al. (1985) and our data to make an Arrhenius plot as shown in Fig 2. Since the 3 sets of data correlated so well ($r^2 = 0.92$) it was concluded that k was independent of texture test, and the correlation applied to any of the potato varieties represented in this plot. Furthermore, we speculate that it was not the absolute value of F which determined degree of cooking but the change in texture as described by F/F_O. We further speculate that the value of F/F_O at optimum degree of cooking was independent of variety. The Arrhenius equation for cooking is:

$$k = k_O\, e^{-E/RT} \qquad (4)$$

where $k_O = 7.813 \times 10^{16}$ min^{-1}; and E/R = 15269 K. This correlation is valid from 74°C to 110°C.

The data for the first part of the curves in Fig. 1, plus the data not shown, were fitted using a least squares fit. The data fit a first order equation, Eq. (2). The correlation coefficients averaged 0.97 ($r^2 = 0.94$). Plotting the rate constants for ge-

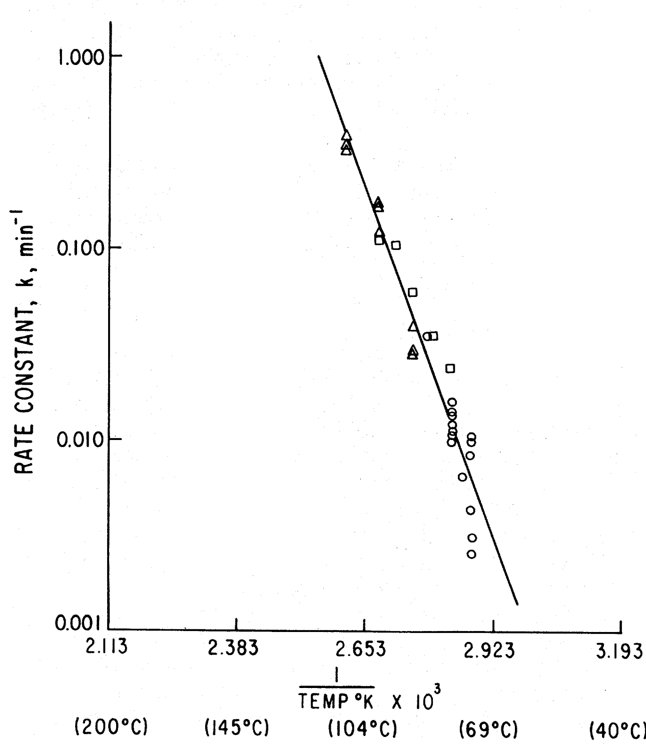

Fig. 2—Arrhenium plot for cooking. $k_O = 7.8 \times 10^{16}$ min^{-1}, E/R = 15269°K. k_O is frequency factor. E/R is activation energy/gas constant. △ Harada et al. (1985); □ Kiyoshi et al. (1978); ○ current work.

latinization plus cooking, as before, in Fig. 3 yielded a straight line with a correlation coefficient of 0.76 (r^2 = 0.58). Since these data are confined to a small temperature span, the correlation coefficient should be less indicative of a good linear fit (Orofino, 1986). Therefore, the correlation coefficient should be lower for gelatinization plus cooking than for cooking. The Arrhenius equation for gelatinization plus cooking is Eq. (4), where $k_O = 1.21 \times 10^{23}$ min^{-1}; and E/R = 19918 K.

It is interesting to note than when the two Arrhenius plots were extrapolated, they intersected at 53°C indicating that below this temperature the kinetics of the texture change should be accounted for by cooking without gelatinization. However, since Pravisani et al. (1985) reported a change in kinetics at 67.5°C the intersection at 53°C should only be considered an approximation. This agrees with the published minimum temperature for gelatinization of about 50–60°C (Talburt and Smith, 1967; Davidson, 1980).

The rate constant, k, for cooking and for cooking plus gelatinization can be calculated from Eq. 4 with the corresponding constants of k_O and E/R. The difference in these values is the rate constant for gelatinization. By calculating various points from these equations, and fitting the Arrhenius equation (Eq. 4) to these points by the method of least squares, the Arrhenius equation for gelatinization was obtained as Eq. (4) with the following constants, $k_O = 7.203 \times 10^{24}$ min^{-1}; and E/R = 21508 K. The activating energy, E, is 43 kcal/mol which compares favorably with the value of 58 kcal/mol reported by Pravisani (1985).

Experiments were run to measure the texture change due to

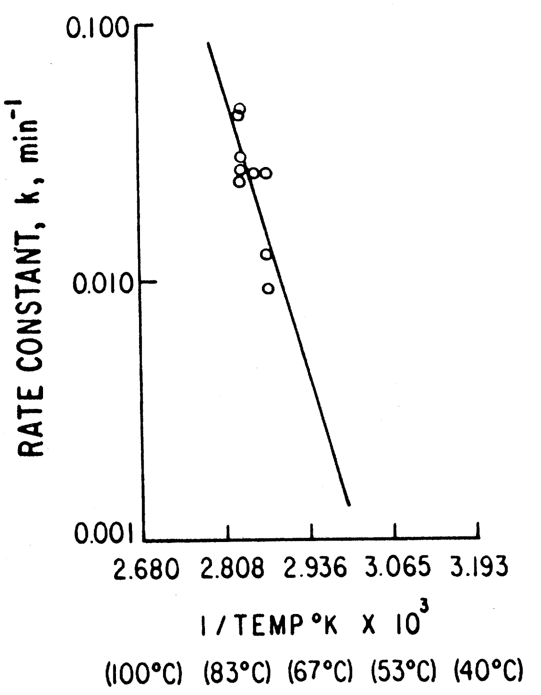

Fig. 3—Arrhenius plot for cooking plus gelatinization. $K_O = 1.2 \times 10^{23}$ min^{-1}, E/R = 19918°K. K_O is frequency factor. E/R is activation energy/gas constant.

retrogradation in which the potatoes were cooled after heating in the water bath. There were essentially no changes detected. The differences in measurement before and after retrogradation were within the limits of experimental error. This line of investigation was terminated with no reportable results.

CONCLUSION

A FIRST ORDER KINETICS MODEL for precooking and cooking of potatoes was presented. Including the data of Harada and of Kiyoshi showed that the kinetics model applies regardless of variety or test method. We propose that the ratio of texture to the original texture, F/F_O, be used as a measure of the amount or degree of cooking.

NOMENCLATURE

α	= diffusivity, m^2/sec.
θ	= time, sec.
B	= 1/2 dice thickness
E/R	= activation energy/gas constant, °K
F	= texture force, texture units
F_O	= texture force of raw potato determined by extrapolation, texture units
k	= rate constant, min^{-1}
k_O	= frequency factor, min^{-1}
T	= temperature, °K
T_1	= bath temperature, °C
T_O	= initial potato dice temperature, °C
T_i	= potato dice temperature, °C
x	= distance from the center, x=0 is the center, x=B is the surface

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